Ermenek Dam and HEPP: Spillway Test & 3D Numeric-Hydraulic Analysis of Jet Collision

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ABSTRACT:
The construction of Ermenek Dam an HEPP, Turkey’s 2nd highest dam in operation, was started in 2002 and finalized in 2010. Two spillways with approximately 500 m long pressure flow tunnels and outlets controlled by radial gates were designed and the tunnel inlets were equipped with roller gates and stop logs for repair works. The reservoir was filled up to maximum operation level in May 2012, then the wet tests of spillways and bottom outlet were conducted. In general, all outlets worked satisfying. The jet from the bottom outlet was safely approaching the narrow gorge of the limestone valley without negative effects to the slopes. The jets from the pressurized tunnels were colliding in the middle of the gorge with energy dissipation in the air. Due to topographic and geologic conditions discovered during construction, it was not possible to design and construct the tunnels in full symmetric form. The tests showed that the jets are colliding in the middle of the gorge under different discharge conditions. But, it was seen that in the lower discharge range (less than 50% gate opening) the expansion angle of the left jet is slightly wider than the right one. At higher gate opening and discharge amounts, the jet expansions are symmetric and the energy dissipation is working well.

To evaluate the reason for the asymmetric jet shape at lower discharge ranges, a 3D numeric-hydraulic analysis was performed. The results of this numeric analysis are presented, described and discussed. Furthermore, the in-situ test for full discharge of 2*495 m³/s and also the safe long time operation of the spillway are discussed.

INTRODUCTION
Recent tests of the spillways at Ermenek Dam showed some asymmetric behavior in jet collision, with the expansion angle of the left jet being slightly wider than the expansion angle of the right jet, thereby reducing energy dissipation at the point of collision (see Figure 1, left). The phenomenon is only observed when the gates are partly opened. At fully open gates (Figure 1, right) both jets are of similar shape and collide with sufficient energy dissipation reflecting a sound design of the complex spillway system despite no hydraulic model test was being used to evaluate and optimize the design. In general, some slight asymmetry in jet formation at certain flow conditions is not considered unusual, especially if a less common design (like Ermenek spillway with steep curved tunnels) is applied.

Figure 1: Ermenek spillway tests (June 2012) with partially open gates (left) and fully open gates (note: pictures are taken from different positions)
The general arrangement of the spillway tunnels and outlets was only possible in an asymmetric form due to topographic and geological conditions.

![Figure 2: Layout of Ermenek spillway tunnels](image)

The different outlet structures are shown in the 3-D sketches below.

![Figure 3: 3-D Model of left and right spillway outlet structures](image)

At the detailed design stage, there was no reason to have doubts on the evaluation performed during final design stage. In fact, the recently performed test of spillway operation have confirmed that the jets collide almost as it was intended in the final design, only the shape of the jet (expansion angle) is different in particular at lower discharges.

In order to identify possible reasons for the asymmetric behavior at partly opened gates and to investigate the potential for optimization, the authors have conducted numerical analysis of the hydraulic conditions in the outlet section using software for Computational Flow Dynamics (CFD). The results of the CFD analysis are presented in this paper.
METHODOLOGY

SOFTWARE AND MODEL GEOMETRY

The CFD calculations have been performed using the software Flow-3D, version 10.0.1. The software is well tested for conditions of pressurized flow as well as for free surface flows. As the investigated jet flow conditions cover motion and mixture of two fluids (i.e. water and air), some model simplifications were necessary. The focus of the numerical analysis was therefore mainly set on the flow conditions in the section between the radial gates and the outlet, with only a very short section of the free jet flow being included in the model domain. Within this domain, the numerical model is expected to provide reliable results. The point of jet collision is not covered by the model.

The model geometry is based on as-built drawings of the outlet structures. For each outlet (left and right) an individual numerical model was built. Both models cover the section from approximately 8.6 m upstream of the radial gate to approximately 45 m upstream of the (theoretical) point of jet collision. The model domains are shown in the figure below. Compared to the right spillway, the outlet tunnel (i.e. the tunnel downstream the radial gate) of the left spillway is approximately 10 m longer and is further extended by a platform directly at the outlet. Also the position of the radial gate relative to the point of jet collision is different. The position of the left gate is approximately 78 m upstream of the collision point, whereas the right tunnel is located only 68 m upstream of the collision point.

In order to investigate the possible hydraulic influence of small geometrical differences between the left and the right structure, it was necessary to build a model with high mesh resolution. Cell sizes of 0.1 m for local y- and z-direction and about 0.1-0.25 m for local x-direction (mean flow direction) were used, leading to a total number of 970200 cells for the left and 743400 cells for the right model, respectively.

BOUNDARY CONDITIONS AND MODEL PARAMETERS

A maximum operation reservoir water level of 694 m a.s.l. was assumed for all simulation scenarios. In case of simulating partially opened gates (0.8 m gate opening; discharge of approximately 80 m³/s on each side) the hydraulic losses were estimated to 0.37 m, resulting in an energy head of 693.63 m a.s.l., which was used as upper boundary condition. For the fully opened gate simulations with a maximum total outflow of 2*495,00 m³/s, the head loss was calculated to 17.78 m, resulting in upper boundary conditions for both outlet structures of 676.22 m a.s.l.

A lower boundary condition of type “outflow” was applied, where the flow leaves the model domain without influencing the solution. Furthermore, the two-parametric RNG-turbulence transport model was used with a one-fluid flow of water, i.e. mixing of water and air, as well as motion of air was disregarded.
PARTIALLY OPENED GATES, AS-BUILT ANALYSIS

Firstly, the simulated left and right spillway flows at 0.8 m gate opening are compared in the cross-section 10 m downstream the radial gate (Figure 5) and 45 m upstream the jet collision point (Figure 6). The flow conditions (hydraulic head, velocity magnitude as well as pressure) immediately downstream of the radial gate are practically the same. In contrast, the jets closer to the collision point already show significant difference in shape and magnitude. This is mainly caused by higher friction losses due to the longer left tunnel section. Closer to the collision point, there is also a small difference in the elevation of the jets caused by different lengths from the outlet / platform to the point of collision, which is 51.2 m (left) and 56.6 m (right).

Figure 5: Hydraulic head 10 m downstream the gate with no crucial differences in shape or magnitude

Figure 6: Velocity magnitude 45 m upstream the collision point with significant differences in elevation, velocity distribution and jet shape

Figure 7 compares general images of the flow velocities which are smaller in the left jet’s bottom area as a result of increased bottom friction at the longer left tunnel / platform.
Secondly, longitudinal profiles of the jets’ upper water surface, the depth averaged flow velocities and the energy heads are illustrated in Figure 8. Up to 10 m downstream the gates, the flow conditions of both spillways are very similar – based on the similar structure geometry in this area. Differences are introduced further downstream where only the left jet is still flowing within the longer structure and is subjected to bottom- and sidewall friction.

Of high relevance are the jets’ hydraulic heads which are plotted against the distance from the point of collision in Figure 9. It clearly shows that the right jet is affected by less hydraulic losses (due to the shorter outlet structure) and therefore has a higher energy level. Furthermore, the right gate is located closer to the collision point resulting in a difference in the total hydraulic head of almost 10 m, evaluated 45 to 50 m away from the collision point!

The hydraulic losses upstream the radial gate are almost negligible due to the low velocities. Flow conditions there are controlled by the gate opening, whereas the very high velocities cause significant losses downstream the gate (in the tunnel but also in the free jet). Therefore, the distance between the gate and the point of collision mainly determines the energy head at the collision point.
Finally, the free jet trajectories were extrapolated by simplified formulas. Starting point for the ballistic extrapolation is the distribution of flow velocities simulated for the lower boundary of the numerical model (45 m upstream of the collision point). There, the following characteristic values have been extracted for streamlines at the upper and lower surface of the jet (see Table 1 and Figure 10):

<table>
<thead>
<tr>
<th></th>
<th>Left Spillway</th>
<th>Right Spillway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity - upper stream line</td>
<td>42 m/s</td>
<td>42 m/s</td>
</tr>
<tr>
<td>Velocity - lower stream line</td>
<td>32 m/s</td>
<td>37 m/s</td>
</tr>
<tr>
<td>Elevation – upper stream line</td>
<td>600.5 m.a.s.l.</td>
<td>600.2 m.a.s.l.</td>
</tr>
<tr>
<td>Elevation – lower stream line</td>
<td>599.8 m.a.s.l.</td>
<td>599.6 m.a.s.l.</td>
</tr>
</tbody>
</table>

Table 1: Maximum and minimum elevation and velocity

Figure 10: Maximum and minimum elevation and schematic velocity for left jet (red) and right jet (blue) 45 m upstream of collision point

Disregarding effects of turbulence, air resistance and intrusion as well as the actual directions of the jets the trajectories for the free jet have simply been derived from gravity acceleration \((g)\) and the horizontal velocity \((v)\) of the flow particles in a stream line by applying the following parabolic formula:

\[
y_i = y_0 - \frac{g}{2 \cdot v^2} \cdot x_i^2
\]

Where:
- \((y_i)\) is the elevation of a flow particle at a horizontal distance \(x_i\) from the outlet
- \((y_0)\) is the elevation of the outlet
- \((v)\) is the flow velocity at the outlet
- \((g)\) is the gravitation (9.81 m/s²)

Despite this strong conceptualization the upper and lower streamlines of both jets allow to explain why the left jet, with reduced velocity of the lower streamline, shows a wider angle of expansion than the right jet (Figure 11).
PARTIALLY OPENED GATES WITH PLATFORM REMOVED

As an attempt to enhance the asymmetric behavior, the longer left outlet structure was analyzed assuming that the existing platform was removed (i.e. cut away at length of approximately 5 m which was the maximum feasible cutting length). The platform is indicated in Figure 3 and Figure 4. Without the platform, the water surface of the left jet would be more similar to the right one (Figure 12). This finding also applies to the deformation of the jet’s cross-sectional shape. Removing the platform might also result in improved energy dissipation when operated at partly opened gates.

However, some difference in the velocity distribution would remain: the left jet is slower at the bottom due to the longer tunnel on the left side and higher friction losses.
FULLY OPENED GATES, AS-BUILT ANALYSIS

In this analysis, the head losses for each spillway tunnel upstream the radial gates were calculated for a maximum outflow of 495,00 m$^3$/s as 17,78 m. From that, the resulting upper boundary condition for both outlet structures was defined as an energy head of 676,22 m a.s.l.

The simulated jets are more uniform and compact than the jets in the simulation with partially opened gates. This can be explained by a much higher total momentum of both jets and relative small hydraulic losses in the tunnel outlet, where only a small outer layer is subject to turbulences and hydraulic losses.

Figure 13 shows that significant difference in flow velocities can only be found at the outer layer of the jets, whereas the core of both water bodies shows nearly the same velocity distribution. This explains why – different from partially opened gates – at fully opened gates efficient energy dissipation at the collision point was observed at the wet test.

SUMMARY AND DISCUSSION

This paper summarizes the CFD-analysis of the observed unsymmetrical spillway jets at the Ermenek Dam. The main causes for the unsymmetrical behavior are:

- the different distances of the radial gates from the collision points
- the different lengths of the outlet structures (section from radial gate to outlet)

The right spillway has a smaller distance from gate to the collision point and a shorter outlet structure length resulting in less hydraulic losses, a jet with higher energy heads and a more uniform distribution of flow velocities. Therefore, the right jet is more concentrated and higher in terms of energy head at the point of collision.

The concrete platform at the outlet of the left spillway is one but not the only reason for the unsymmetrical jets. Removing the concrete platform could partly improve the situation when the gates are partly open, but some asymmetry would remain as the length of the left outlet structure cannot be shortened and the distance from gate to collision point cannot be adjusted anymore. As the improvement by removing the concrete platform was rather small and the effects are associated with some uncertainty, it was recommended leaving it in place.
The simulations also showed that the asymmetric behavior of the jets is most pronounced at low discharges (i.e. at partly opened gates). During such reduced spillway flows the hydraulic losses upstream of the gates are almost negligible, whereas downstream of the gates the losses due to friction at the tunnel bottom and side walls dissipate a significant part of the total energy. Consequently, a similar length of the flow section downstream of the gates is crucial for symmetric jet formation.

For higher flows the hydraulic losses downstream of the radial gate only dissipate a minor part of the total momentum of the flow, which is much higher than at partly opened gates. Furthermore, also the tunnel sections upstream of the radial gates cause significant hydraulic losses. Therefore, during high flows the length of the flow section downstream of the radial gate is less important for symmetric jet formation. This explains why during spillway wet tests with fully opened gates jet collision was symmetrical.

The CFD-analysis itself provided clear and plausible results, although some features as the mesh resolution for the boundary layer and the velocity profile computation at the wall (y+ Criterion) should be considered in more detail.

Until late 2014, the spillway was tested successfully several times at different gate opening scenarios. Also, the spillway was operated for nearly one month at maximum operation level and no negative effects to the structures and to the gorge at the jet collision area could be encountered.

As a general lesson learned from this analysis, asymmetric geometries of jet collision spillway outlets cannot be recommended. If however such asymmetry cannot be avoided, the spillway performance shall be analyzed hydraulically by means of CFD-techniques or model tests at the earliest possible phase in order to prevent unfavorable conditions.